Searches for Heavy Higgs in ATLAS (non–MSSM)

A. Schaffer
LAL, Univ Paris-Sud, IN2P3/CNRS, Orsay, France
On behalf of the ATLAS Collaboration

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Heavy Higgs bosons are predicted in many BSM models

Two examples are:

- Two Higgs Doublet Model (2HDM): h, H, A, H^+, H^-
- EW Singlet Model: h, H

Report here on diboson searches - these are performed in fairly model independent ways:

- Narrow Width Approximation (NWA)
  - 4 MeV (width << detector resolution)
- Large Width Assumption (LWA)
  - with widths up to 15% of the mass (no interference treatment)
- Production modes:
  - gluon-gluon fusion (ggF)
  - vector boson fusion (VBF)

Using the latest 13 TeV data sets of 2015 + 2016

- sensitivity is often exceeding results published with 7/8 TeV data and extends to higher mass range
## Overview of diboson modes and mass range

<table>
<thead>
<tr>
<th>Channel</th>
<th>Lumi (fb$^{-1}$)</th>
<th>Mass range</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ→4l NWA</td>
<td>14.8</td>
<td></td>
<td>ATLAS-CONF-2016-079</td>
</tr>
<tr>
<td></td>
<td>LWA</td>
<td></td>
<td>ATLAS-CONF-2016-079</td>
</tr>
<tr>
<td>ZZ→llvv NWA</td>
<td>13.3</td>
<td></td>
<td>ATLAS-CONF-2016-056</td>
</tr>
<tr>
<td>ZZ→llqq NWA</td>
<td>13.2</td>
<td></td>
<td>ATLAS-CONF-2016-082</td>
</tr>
<tr>
<td>ZZ→vvqq NWA</td>
<td>13.2</td>
<td></td>
<td>ATLAS-CONF-2016-082</td>
</tr>
<tr>
<td>WW→lvlv NWA</td>
<td>13.2</td>
<td></td>
<td>ATLAS-CONF-2016-074</td>
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<tr>
<td></td>
<td>LWA</td>
<td></td>
<td>ATLAS-CONF-2016-074</td>
</tr>
<tr>
<td>WW→lvqq NWA</td>
<td>13.2</td>
<td></td>
<td>ATLAS-CONF-2016-062</td>
</tr>
<tr>
<td>γγ NWA/LWA</td>
<td>15.4</td>
<td></td>
<td>ATLAS-CONF-2016-059</td>
</tr>
<tr>
<td>ZZ→llγ NWA</td>
<td>13.3</td>
<td></td>
<td>ATLAS-CONF-2016-044</td>
</tr>
<tr>
<td>ZZ→qqγ NWA</td>
<td>3.2</td>
<td></td>
<td>arXiv:1607.06363</td>
</tr>
</tbody>
</table>

The graph shows the mass range for different channels, with an emphasis on the mass range for the Higgs boson ($m_H$) from $10^2$ to $3000$ GeV.
Sensitivity Comparison for Different Modes

- Compare hadronic and semi-leptonic final states for 13 TeV, 3.2 fb\(^{-1}\) ([arXiv:1606.04833])
  - Approx ordering: lνqq / qqqq / llqq+vvqq
  - Decays modes have no overlap
  - All but qqqq updated here with higher integrated luminosity

- Compare \(H\rightarrow ZZ\) modes for 8 TeV, 20.3 fb\(^{-1}\) ([EPJC])
  - 4l best below ~500 GeV
  - llνν close to llqq+vvqq
General Search Strategy

- Optimized event selection for a given heavy Higgs boson signal
- Data-driven background estimation/control for dominant backgrounds whenever possible
- Statistical analysis based on either fully reconstructed mass $m_H$ or transverse mass $m_T$ distributions from signal (and control) regions
- Hadronic Z/W decays reconstructed with
  - resolved small-R ($\Delta R=0.4$) jet at low mass
  - merged large-R ($\Delta R=1$) jet at high mass

Use energy correlation ratio $D_2^{(\beta=1)}$ to infer two-prong jet substructure

ATL-PHYS-PUB-2015-033
Decay mode with fully reconstructed leptons

- **ZZ→4l (4µ, 2e2µ, 4e)**
  - \(m_{4l}\) (apply Z mass constraint)
  - \(\Rightarrow\) excellent mass resolution

- ggF & VBF for NWA signal

- LWA signal (1%, 5%, 10%)

- 4 signal categories
  - VBF: \(m_{jj} > 400\ \text{GeV}, |\Delta\eta_{jj}| > 3.3\)
  - otherwise ggF (4µ, 2e2µ, 4e)

- Dominant background:
  - non-resonant ZZ*
Decay mode with fully reconstructed leptons

95% CL upper limits on $\sigma \times B(H \rightarrow ZZ)$

NWA valid for models with width < 0.5%

When fitting ggF, VBF is left free, and vice-versa

(Unshown: 1% and 5% available)
Leptonic Decay Modes with Neutrinos

- **ZZ→llνν, WW→lνlν**
  - Cannot be fully reconstructed
  - Use $m_T$ instead:

$$m_{ZZ}^Z = \sqrt{\left(\sqrt{m_Z^2 + \mid p_T^\ell \mid^2} + \sqrt{m_Z^2 + \mid E_T^{miss} \mid^2}\right)^2 - \mid p_T^\ell + E_T^{miss} \mid^2}$$

$$m_T = \sqrt{2p_T^\ell E_T^{miss} \left[1 - \cos \Delta \phi(p_T^\ell, E_T^{miss})\right]}$$

**ZZ signal region (SR)**

**WW SR for quasi-inclusive ggF new for ICHEP**

**WW SR for 1-jet VBF new for ICHEP**

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Leptonic Decay Modes with Neutrinos

95% CL upper limits on \( \sigma \times B(H \rightarrow ZZ/WW) \)

**ATLAS Preliminary**

- Observed
- Expected (CLs)

\( \sqrt{s} = 13 \) TeV, \( 13.2 \) fb\(^{-1} \)

**H → ZZ → \( l\nu l\nu \)**

- \( \sigma \times B(H \rightarrow ZZ) \) [fb]

**Observed**

- Expected \( \pm 1\sigma \)

**Expected**

- \( \pm 2\sigma \)

\( \sigma \times B(H \rightarrow WW) \) [pb]

- \( m_H \) [GeV]

**Observed (CLs)**

- Expected (CLs)

**WW: ggF NWA**

**WW: VBF NWA**

**WW: ggF LWA - 5%, 10%, 15% \times m_H**
Semi-Hadronic Decay Modes

- $ZZ\rightarrow llqq$, $vvqq$, $WW\rightarrow lvqq$
  - $llqq$: resolved and merged jets
  - $vvqq$, $lvqq$: merged jet only
  - Resolved jet analysis subdivided into b-tagged and untagged categories
  - Merged jet analysis has two categories:
    1. High-purity: two-prong substructure
    2. Low-purity: otherwise
  - $llqq$ VBF: $m_{jj} > 600$ GeV, $|\Delta\eta_{jj}| > 3.1$

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Semi-Hadronic Decay Modes

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$lvqq$

- $E_T^{\text{miss}} = 460$ GeV,
- $p_T^\mu = 270$ GeV
- $m_{l\nu J} = 1.56$ TeV

$llqq$, high purity

$vvqq$, high purity

Jet $p_T$: 810 GeV
270 GeV
Semi-Hadronic Decay Modes (95% CL upper limits)

ATLAS Preliminary

- Observed (CLs)
- Expected (CLs)

\( ggF - llqq \)

\( gg \rightarrow H \rightarrow ZZ \rightarrow llqq \)

\( \sqrt{s} = 13 \text{ TeV}, 13.2 \text{ fb}^{-1} \)

- \( \pm 1 \sigma \)
- \( \pm 2 \sigma \)

\( m_H \) [GeV]

\( \sigma \times BR (\text{Scalar} \rightarrow WW) \) [pb]

ATLAS Preliminary

- Observed 95% CL upper limit
- Expected 95% CL upper limit

\( gg \rightarrow H \rightarrow ZZ \rightarrow vv qq \)

\( \sqrt{s} = 13 \text{ TeV}, 13.2 \text{ fb}^{-1} \)

- Expected limit (\( \pm 1 \sigma \))
- Expected limit (\( \pm 2 \sigma \))

\( m_{\text{Scalar}} \) [GeV]
Diphoton Decay Mode

- Excess seen in 2015 dataset (3.2 fb\(^{-1}\)):
  - With reprocessing (energy and track reco):
    - Excess change: 3.9\(\sigma\) \(\rightarrow\) 3.4\(\sigma\)
    - \(m_{\gamma\gamma} (\Gamma_{\gamma\gamma})\): 750 GeV (6\%) \(\rightarrow\) 730 GeV (8\%)
- No excess seen in 2016 data (12.2 fb\(^{-1}\))
- 2015+2016 combined limits:
  - Widths evaluated: NWA, 2\%, 6\%, 10\%
  - Largest excess near 750 GeV:
    - 2.3\(\sigma\) @ 710 GeV (10\% width)

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**Z + γ Decay modes**

- **Zγ→llγ (13.3 fb⁻¹), qqγ (3.2 fb⁻¹ published)**
  - qq is a large-R (boosted) jet
- **Dominant backgrounds:**
  - llγ: non-resonant Z+γ (90%) + Z+jets (10%)
  - qqγ: γ +jets
  - Modeled with:
    
    \[ f_{\text{bkg}}(m_{Z\gamma}) = N(1 - x^k)p_1 + \xi p_2 x^p_2 \]

    \[ x = m_{Z\gamma}/\sqrt{s} \]
    
    \[ k = 1/3, \quad \xi = 0 \quad \text{for llγ} \]
    
    \[ k = 1, \quad \xi \sim 10 \quad \text{for qqγ} \]

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**ATLAS Preliminary**

- **pp→X→Zγ, Z→e⁺e⁻, μ⁺μ⁻**
  - \( \sqrt{s} = 13 \text{ TeV}, 13.3 \text{ fb}^{-1} \)
  - Events / 20.0 GeV

**ATLAS**

- **pp→X→Zγ, Z→q̅q**
  - \( \sqrt{s}=13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)
  - Data
  - Background-only fit, b

**Data - b**

- Events / 20.0 GeV

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95% CL upper limits on $\sigma \times \text{BR}(H \rightarrow Z\gamma)$

$\Rightarrow$ leptonic (hadronic) decay has better sensitivity at low (high) mass
A Heavy Higgs boson has been searched for using up to 14.8 fb-1 @ 13 TeV in many diboson decay modes:

- fully leptonic (ZZ\rightarrow 4l) including neutrinos (ZZ\rightarrow llvv, WW\rightarrow l\nu l\nu)
- semi-hadronic (ZZ\rightarrow llqq, \nu\nu qq, WW\rightarrow l\nu qq)
- with \gamma s (\gamma\gamma, Z\gamma\rightarrow ll\gamma, qq\gamma)
- fully hadronic (VV\rightarrow qqqq)

No significant deviation has been found

- Stringent upper limits have been set for:
  - ggF and VBF production modes
  - for NWA and LWA line shapes over a wide range

The 2016 data taking is now complete with \sim 36.5 fb\(^{-1}\) available for physics from 2015/16 (more than \times 2.5 in statistics)

- good perspective for discovery or more stringent constraints

- work on-going to include interference effects
Backups
Interference Considerations

- Time has not allowed to include interference effects
  - It has been considered more important to include additional data

- Interference effects are in general small for the widths considered
  - The lower mass limit has in some cases been increase to avoid ~10% effects

- Planning to include interference effects for h, H and background for the spring publications
  - Will depend upon the H couplings, and so model-dependent